AdS/TC toward the LHC

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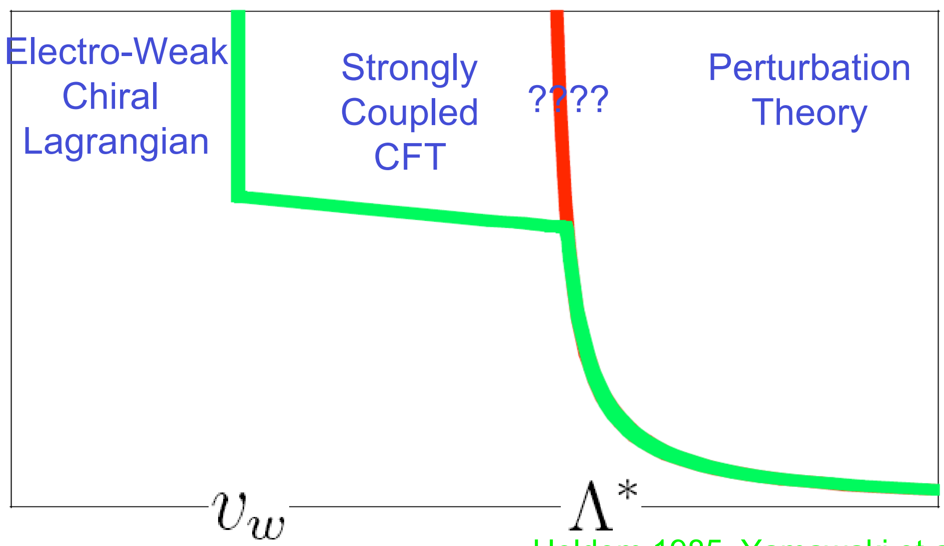
Outline

- Introduction: Walking (phenomenological definition).
- 5D Minimal Model (AdS/CFT).
- Precision Electro-weak (S parameter!).
- LHC Signals and Reach (spin-1).

4D-DEWSB: WALKING TC



Holdom 1985, Yamawaki et al. 1986, Appelquist et al. 1986

- Quasi-Conformal behavior in the IR.
- TWO (or more…) dynamically generated scales.
- d=2 chiral condensate (large top mass)
- Higher-Order operators suppressed:
- SM fermions elementary (GIM, no FCNC)

$$\Lambda^* \gtrsim 5\,\mathrm{TeV}$$

$$3 \times 10^{-3} \gtrsim \hat{S}_{nc} \simeq \left(\frac{v_w}{\Lambda^*}\right)^2$$

Computational technique ? AdS/CFT (large-N additional assumption)

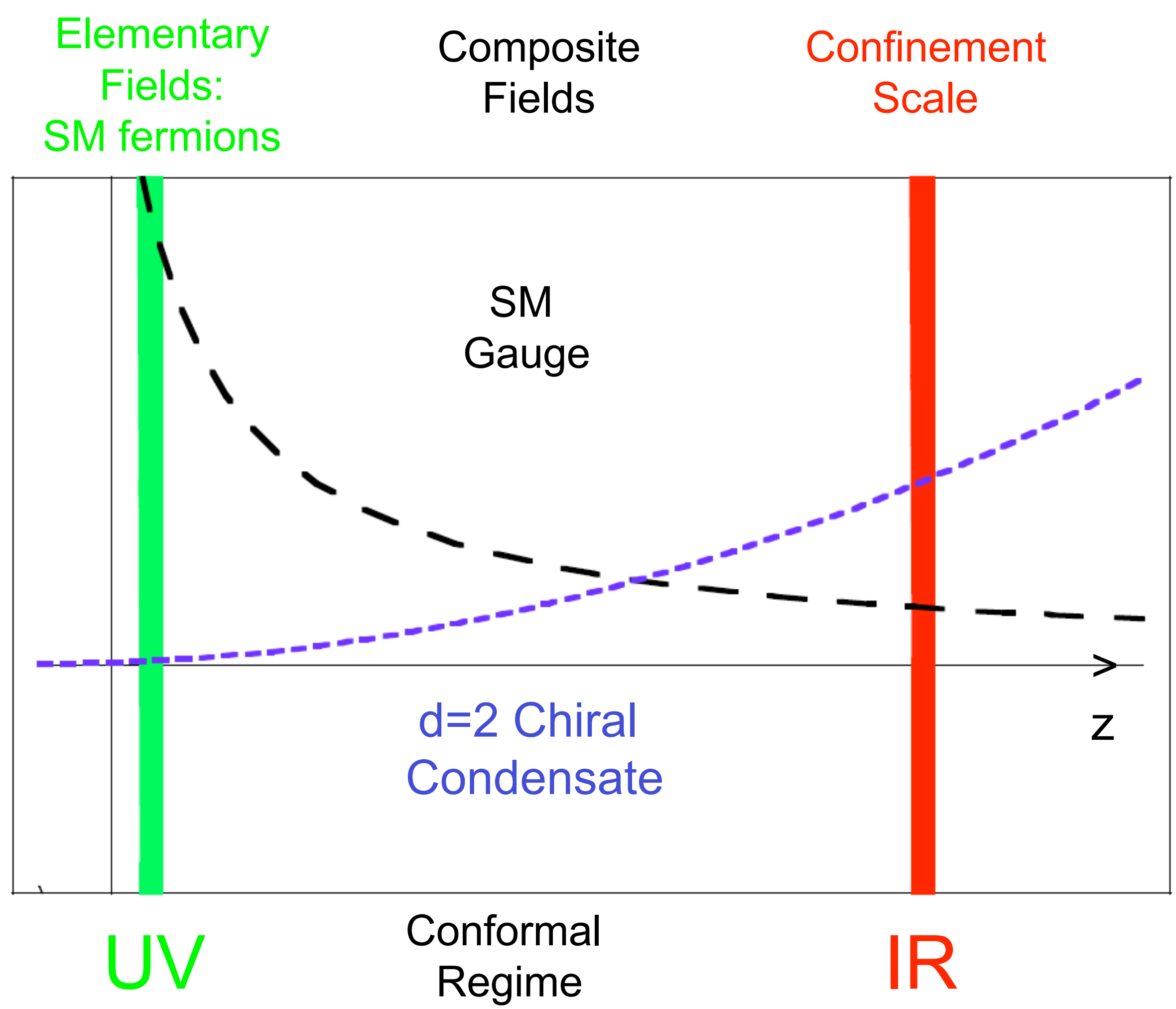
Program of AdS/TC

- Walking TC (IR fixed point, conformal energy window at large coupling, large anomalous dimension for chiral condensate…) has two problems: precision EW and CALCULABILITY!

  Holdom 1985, Yamawaki et al. 1986, Appelquist et al. 1986

- Use AdS/CFT and extend EFT: Simple AdS/TC 5D Model, Few Parameters.
- Devise Computational Technique (2-point Functions at Large-N from boundary-boundary correlators).
- Compute Observables, focus on Generic Problems of TC.
- Identify Parameter-Space Region Compatible with Data.
- Predict TeV-Scale Physics (production and detection at LHC).

A Model: Pictionary



A Model: Action

$$
\begin{aligned}
\mathcal{S}_5 &= \int \mathrm{d}^4x \int_{L_0}^{L_1} \mathrm{d}z\,\sqrt{G}\Big[\ \left(G^{MN}(D_M\Phi)^\dagger D_N\Phi - M^2|\Phi|^2\right) \\
&\quad \left(-\frac{1}{2}\mathrm{Tr}\left(W_{MN}W_{RS}\right) - \frac{1}{4}B_{MN}B_{RS}\right)G^{MR}G^{NS}\Big]
\end{aligned}
$$

$$\Phi \sim (2, 1/2)$$

$$SU(2)_L \times U(1)_Y$$

$$
\begin{aligned}
\mathcal{S}_4 &= \int \mathrm{d}^4x \int_{L_0}^{L_1} \mathrm{d}z\,\sqrt{G}\Big[\delta(z-L_0) \\
&\quad \left[-\frac{1}{2}D\mathrm{Tr}\left[W_{\mu\nu}W_{\rho\sigma}\right] - \frac{1}{4}DB_{\mu\nu}B_{\rho\sigma}\right]G^{\mu\rho}G^{\nu\sigma} \\
&\quad -\delta(z-L_0)\,2\lambda_0\left(|\Phi|^2 - \frac{\mathrm{v}_0^2}{2}\right)^2 \\
&\quad -\delta(z-L_1)\,2\lambda_1\left(|\Phi|^2 - \frac{\mathrm{v}_1^2}{2}\right)^2\Big],
\end{aligned}
$$

- Kinetic boundary terms needed for renormalization.
- Boundary terms introduce spontaneous EWSB.

$$\mathrm{d}s^2 = \left(\frac{L}{z}\right)^2\left(\eta_{\mu\nu}\mathrm{d}x^\mu\mathrm{d}x^\nu - \mathrm{d}z^2\right)$$

EWSB

- Bulk VEV for “Higgs”: $$\langle\Phi\rangle = \frac{\mathrm{v}(z)}{\sqrt{2}}\begin{pmatrix}0\\1\end{pmatrix}$$
- Bulk Equations: $$\partial_z\left(\frac{L^3}{z^3}\partial_z \mathrm{v}\right) - \frac{L^5}{z^5}M^2\mathrm{v} = 0$$
- Saturate BF: $$\boxed{M^2 = -4/L^2}$$
- Solution: $$\mathrm{v}(z) = Az^2 + Bz^2\log(z/L)$$
- Non-linear EFT: $\lambda_i \to +\infty$ $\quad || \quad$ $\begin{cases}\mathrm{v}(L_0) = \mathrm{v}_0\,, \\ \mathrm{v}(L_1) = \mathrm{v}_1\,,\end{cases}$
- Boundary terms: $\dfrac{\mathrm{v}_0}{L_0^2} = \dfrac{\mathrm{v}_1}{L_1^2}$ $\quad || \quad$ $B = 0$

No Explicit (hard) breaking of Conformal Symmetry

- Finally d=2: $$\boxed{\mathrm{v}(z) = \frac{\mathrm{v}_1}{L_1^2}z^2 = \frac{\mathrm{v}_0}{L_0^2}z^2}$$

Electro-Weak Phenomenology

- Neutral Components, Define:

$$\begin{cases} V^M \equiv \dfrac{g' W_3^M + g B^M}{\sqrt{g^2 + g'^2}} \\ A^M \equiv \dfrac{g W_3^M - g' B^M}{\sqrt{g^2 + g'^2}} \end{cases}$$

- Factorize and Fourier Transform:

  (unitary gauge)

$$A^\mu(q,z) \equiv A^\mu(q) v_Z(z,q)$$

(and so on…)

- Bulk Equations:

$$\partial_z \frac{L}{z} \partial_z v_i - \mu_i^4 L z v_i = -q^2 \frac{L}{z} v_i \qquad \begin{cases} \mu_W^4 = 1/4 g^2 \mathrm{v}_0^2 / L^2 \\ \mu_Z^4 = 1/4 (g^2 + g'^2) \mathrm{v}_0^2 / L^2 \end{cases}$$

- Neumann boundaries at IR: boundary action=0 at IR.
- Boundary Action at UV defines polarizations:

$$\mathcal{L} = \frac{P_{\mu\nu}}{2} A_i^\mu \pi_{ij}(q^2) A_j^\nu + g_4^a J_{a\mu} A_a^\mu \qquad \begin{cases} \hat{S} \equiv \dfrac{g_4}{g_4'} \pi'_{WB}(0) \,, \\ \hat{T} \equiv \dfrac{1}{M_W^2} \left(\pi_{WW}(0) - \pi_+(0) \right) \,, \end{cases}$$

$$
\begin{aligned}
\frac{\pi_+}{\mathcal{N}^2} &= Dq^2 + \frac{\partial_z v_W}{v_W}(q^2, L_0)\,, \\
\frac{\pi_{BB}}{\mathcal{N}^2} &= Dq^2 + \frac{g^2}{g^2+g'^{\,2}}\frac{\partial_z v_v}{v_v}(q^2, L_0) + \frac{g'^{\,2}}{g^2+g'^{\,2}}\frac{\partial_z v_Z}{v_Z}(q^2, L_0)\,, \\
\frac{\pi_{WB}}{\mathcal{N}^2} &= \frac{gg'}{g^2+g'^{\,2}}\left(\frac{\partial_z v_v}{v_v}(q^2, L_0) - \frac{\partial_z v_Z}{v_Z}(q^2, L_0)\right)\,, \\
\frac{\pi_{WW}}{\mathcal{N}^2} &= Dq^2 + \frac{g'^{\,2}}{g^2+g'^{\,2}}\frac{\partial_z v_v}{v_v}(q^2, L_0) + \frac{g^2}{g^2+g'^{\,2}}\frac{\partial_z v_Z}{v_Z}(q^2, L_0)\,,
\end{aligned}
$$

- Tree-level results: small gauge couplings (large-Nc)
- Pure boundary terms universal: T parameter calculable.
- No pure boundary in WB polarization: S parameter calculable.

Regularization

- Expand for $L_0 \longrightarrow 0$

$$\begin{cases} \dfrac{\partial_z v_v}{v_v}(q^2, L_0) &= \underline{q^2 L_0}\left(\dfrac{\pi}{2}\dfrac{Y_0(qL_1)}{J_0(qL_1)} - \underline{\left(\gamma_E + \ln\dfrac{qL_0}{2}\right)}\right) \\ \dfrac{\partial_z v_Z}{v_Z}(q^2, L_0) &= \underline{L_0}\left\{\mu_Z^2 - \underline{q^2\left[\gamma_E + \ln(\mu_Z L_0)\right.} + \dfrac{1}{2}\psi\left(-\dfrac{q^2}{4\mu_Z^2}\right) - \left.\dfrac{c_2}{2c_1}\Gamma\left(-\dfrac{q^2}{4\mu_Z^2}\right)\right]\right\} \end{cases}$$

- From Neumann at IR:

$$\begin{cases} c_1 &= 2L\left(-1+\dfrac{q^2}{4\mu_Z^2}, \mu_Z^2 L_1^2\right) + L\left(\dfrac{q^2}{4\mu_Z^2}, -1, \mu_Z^2 L_1^2\right), \\ c_2 &= -U\left(-\dfrac{q^2}{4\mu_Z^2}, 0, \mu_Z^2 L_1^2\right) + \dfrac{q^2}{2\mu_Z^2} U\left(1-\dfrac{q^2}{4\mu_Z^2}, 1, \mu_Z^2 L_1^2\right) \end{cases}$$

- Notice: divergence is universal!

Renormalization

- Define, at finite UV cut-off:

$$\begin{cases} D = L_0 \left(\ln \dfrac{L_0}{L_1} + \dfrac{1}{\varepsilon^2} \right) \\ \mathcal{N}^2 = \varepsilon^2 / L_0 \end{cases}$$

- Cut-off dependence disappears, take the limit of infinite UV cut-off ($L_0 \to 0$).

- SM Gauge couplings kept fixed:

$$\boxed{g_4^{(\prime)\,2} = \varepsilon^2 g^{(\prime)\,2} / L}$$

Experimental and Theoretical Bounds

- Experiment:

$$\begin{cases} \hat{S}_{exp} = (-0.9 \pm 3.9) \times 10^{-3}\,, \\ \hat{T}_{exp} = (2.0 \pm 3.0) \times 10^{-3}\,, \end{cases}$$

- Theory:

$$\begin{cases} \hat{S} \simeq \frac{1}{e} M_W^2 L_1^2, \\ \hat{T} \simeq \frac{M_Z^2 - M_W^2}{6\varepsilon^2} L_1^2 = \frac{e}{6\varepsilon^2} \frac{M_Z^2 - M_W^2}{M_W^2} \hat{S} \end{cases}$$

- Bounds:

$$\boxed{\frac{1}{L_1} > \frac{M_W}{\sqrt{e\hat{S}_{\max}}} = 890\,\mathrm{GeV}}$$

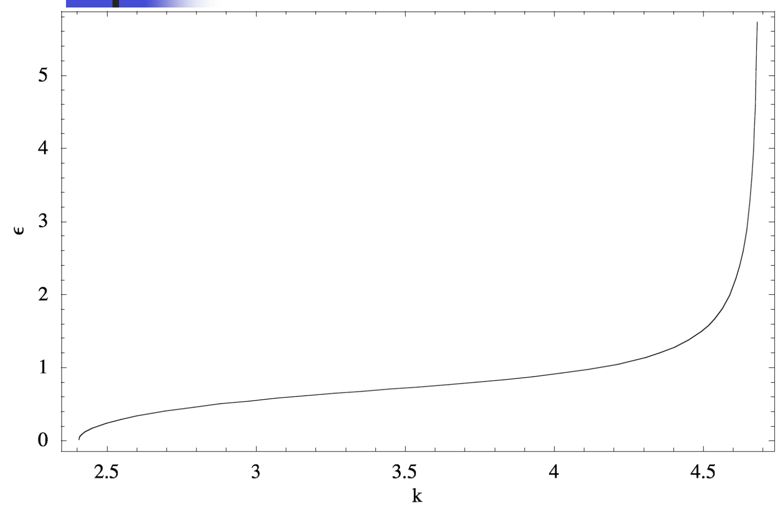
- Perturbation theory in 5D (large-N !):

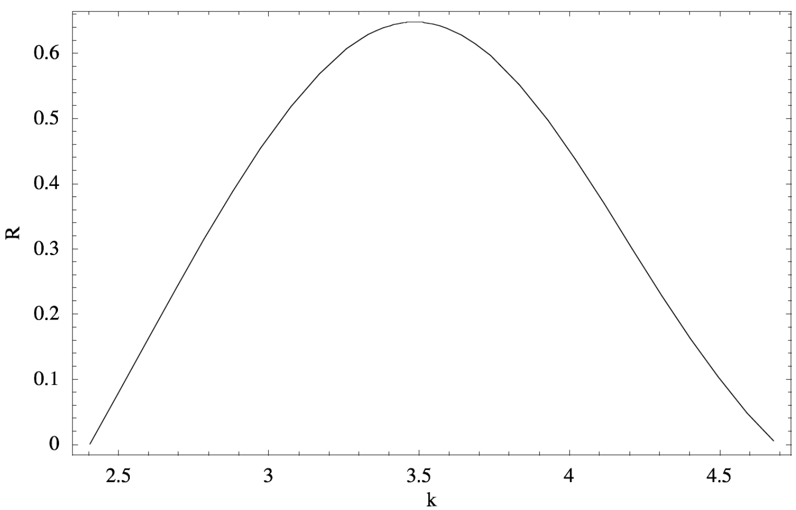
$$\boxed{\varepsilon > 1/2 \;\; (g/\sqrt{L} < 1.3)}$$

Spin-1 Excited States Phenomenology

- 4 Degenerate States in few TeV range.
- Quantum number as SM gauge bosons.
- 2 free parameters (confinement scale and coupling strength).
- Compute width (WW and ff final state).
- Look at 2-lepton final state at LHC.
- Discovery neutral states: easy! (10/fm).
- High luminosity: discovery of charged states, measurement of effective coupling, study of helicity structure, resolving 4 bosons.

Model Parameters





How to measure the fundamental parameters?

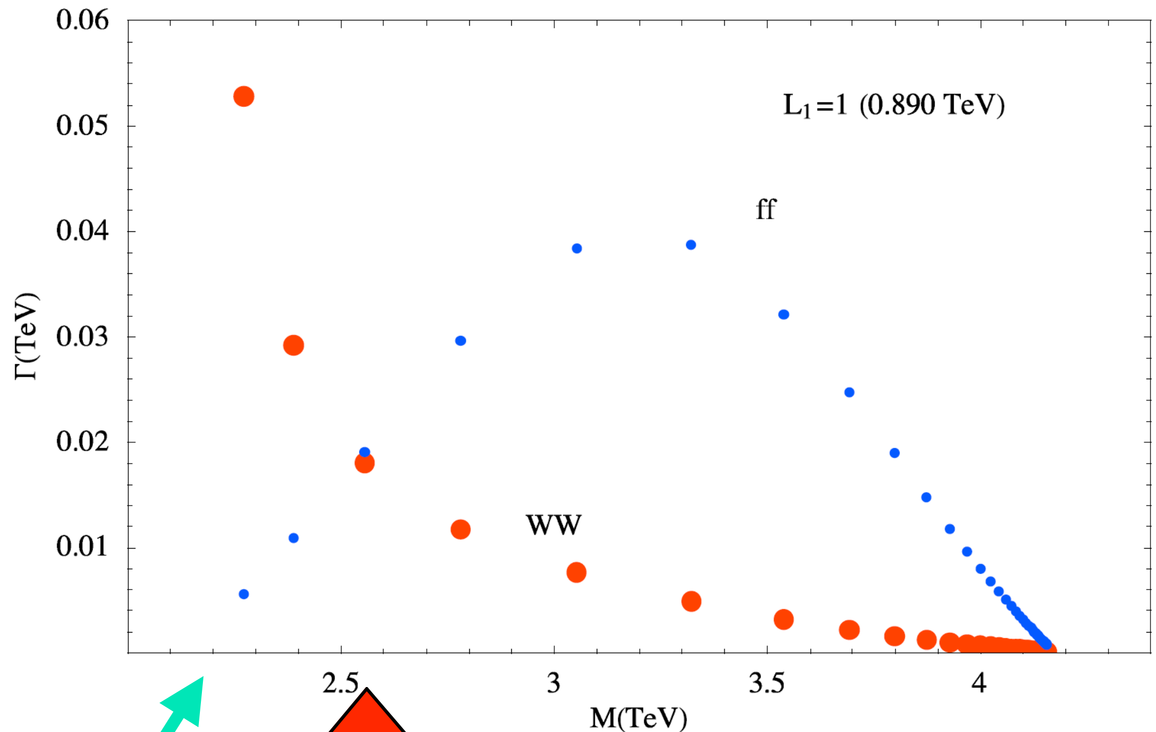
$$k = M_{\gamma'} L_1 \qquad R = |e_4'/e_4|^2$$

$$\frac{1}{\varepsilon^2} = \gamma_E + \ln\frac{k}{2} - \frac{\pi}{2}\frac{Y_0(k)}{J_0(k)}$$

$$e_4' = e_4 \frac{v_v(L_0, M_{\gamma'})}{v_v(L_0, 0)}$$

$$\left(\frac{e_4}{e_4'}\right)^2 = \frac{\left(\pi^2\left(Y_0(k)Y_2(k) - Y_1(k)^2\right)k^2 + 4\right)J_0(k)^2 + \pi Y_0(k)\left(\pi J_2(k)Y_0(k)k^2 + 4\right)J_0(k)}{4J_0(k)\left(\pi Y_0(k) - 2J_0(k)\left(\log\left(\frac{k}{2}\right) + \gamma\right)\right)}$$
$$-\frac{2\pi^{3/2}Y_0(k)G^{2,1}_{2,4}\left(k^2 \,\middle|\, \begin{matrix}1, \frac{3}{2}\\ 1, 2, 0, 0\end{matrix}\right)J_0(k) - k^2\pi^2 J_1(k)^2 Y_0(k)^2}{4J_0(k)\left(\pi Y_0(k) - 2J_0(k)\left(\log\left(\frac{k}{2}\right) + \gamma\right)\right)}. \qquad (59)$$

Decay Rates

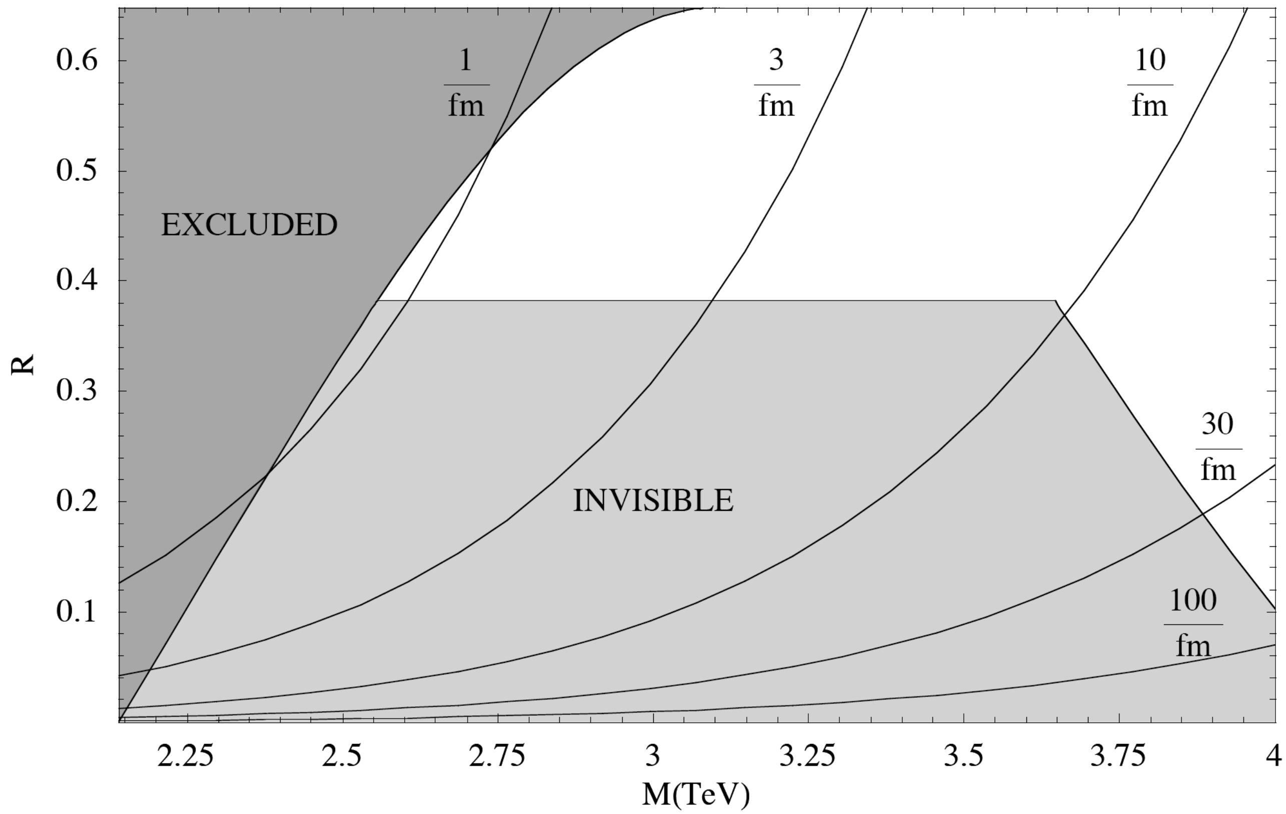


Strong Decays Can Be Neglected When Large-N Applies!!!

QCD-like TC

$$\varepsilon > 1/2 \; (g/\sqrt{L} < 1.3)$$

LHC reach



$$pp \to X + \mu^+\mu^-$$

N>10 Events.

LHC reach

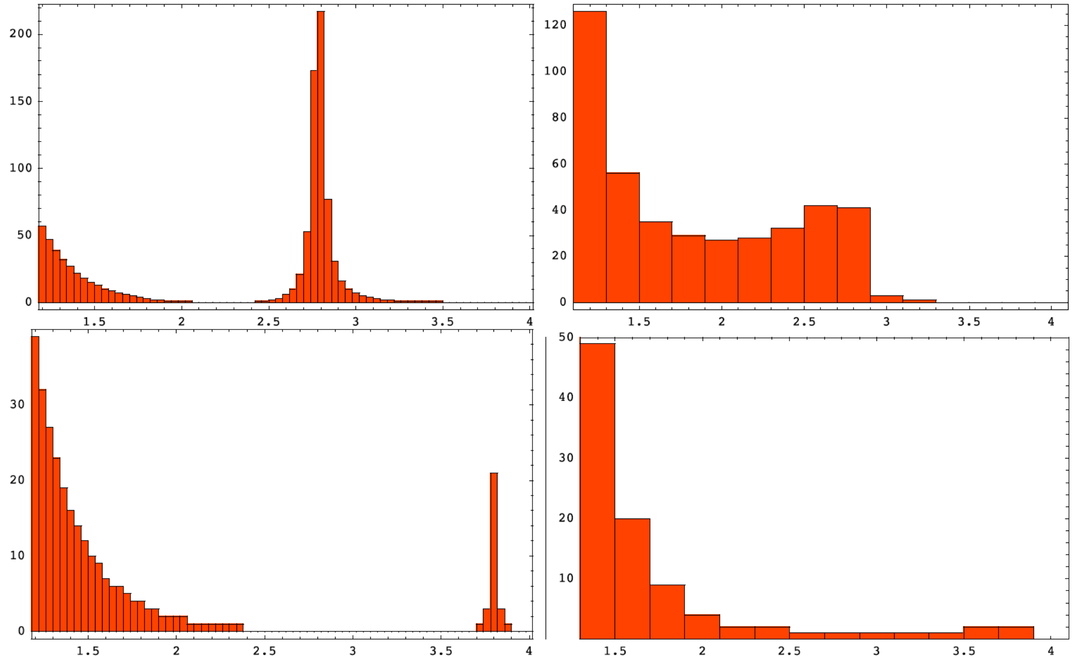


FIG. 5: Number of events expected at the LHC for integrated luminosity of 100 fm^{-1} and for $L_1 = 1/0.89\ \mathrm{TeV}^{-1}$, as a function of the recostructed $\sqrt{\hat{s}}$ for $\mu^+\mu^-$ final state (left diagrams) and of m_T for $\mu^+\nu_\mu$ (right diagrams). Upper diagrams for $\varepsilon = 0.6$ (or equivalently for $M_{\gamma'} = 2.78$ TeV and $R = 0.55$). Lower diagrams for for $\varepsilon = 1.1$ (or equivalently for $M_{\gamma'} = 3.80$ TeV and $R = 0.25$).

Outlook

- Preparing for LHC: AdS/CFT great computational tool for dynamical EWSB (AdS/TC).
- Minimal (walking) model: large-N, (moderate) hierarchy between confinement and symmetry breaking, d=2 chiral condensate.
- Precision EW calculable, allowed region of parameter space exists.
- No FCNC (SM fermions all universal).
- Simple LHC signature: new spin-1 states, decaying to two SM fermions.